

Stardust encounters comet 81P/Wild 2

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[1] Stardust successfully encountered comet 81P/Wild 2 on 2 January 2004 at a distance of 236.4 ± 1 km. All encounter investigations acquired valuable new and surprising findings. The time-of-flight spectrometer registered 29 spectra during flyby and measured the first negative ion mass spectra of cometary particles. The dust detectors recorded particles over a broad mass range, 10^{-11} to 10^{-4} g. Unexpectedly, the dust distribution along Stardust's flight path was far from uniform, but instead occurred in short "bursts," suggesting in-flight breakup of fragments ejected from the nucleus. High-resolution, stunning images of the Wild 2 surface show a diverse and complex variety of landforms not seen from comets 1P/Halley and 19P/Borrelly or icy satellites of the outer solar system. Longer-exposure images reveal large numbers of jets projected nearly around the entire perimeter of the nucleus, many of which appear to be highly collimated. A triaxial ellipsoidal fit of the Wild 2 nucleus images yields the principal nucleus radii of $1.65 \times 2.00 \times 2.75$ km (± 0.05 km). The orientations and source locations on the nucleus surface of 20 highly collimated and partially overlapping jets have been traced. There is every indication that the expected samples were successfully collected from the Wild 2 coma and are poised for a return to Earth on 15 January 2006.

INDEX TERMS: 6210 Planetology: Solar System Objects: Comets; 6213 Planetology: Solar System Objects: Dust; 6008 Planetology: Comets and Small Bodies: Composition; 6015 Planetology: Comets and Small Bodies: Dust; 3655 Mineralogy and Petrology: Major element composition; *KEYWORDS:* comet sample return, Stardust mission, Wild 2

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1. Introduction

[2] Stardust, NASA's fourth Discovery mission, after a five year cruise successfully encountered comet 81P/Wild 2 on 2 January 2004 with a closest approach at a distance of 236.4 ± 1 km. Stardust was launched on 7 February 1999 with the primary goal of collecting particulate coma samples from comet Wild 2 for return to Earth [Brownlee et al., 2003]. At the encounter, four other in situ investigations were operated, including the Comet and Interstellar Dust Analyzer (CIDA) [Kissel et al., 2003], the Dust Flux

Monitor Instrument (DFMI) [Tuzzolino et al., 2003], Navigation Camera (NavCam) [Newburn et al., 2003a] and two-way Doppler and spacecraft attitude control system as Dynamic Science [Anderson et al., 2003]. The collected samples are scheduled to return to the Utah Test & Training Range by direct reentry in a capsule on 15 January 2006. After a preliminary examination, these samples will be made available to the scientific community for detailed study for decades to follow [Brownlee et al., 2003; Tsou et al., 2003]. In this paper we provide a review of the factors and events that resulted in the parameters of the Stardust encounter with Wild 2 and provide an overview of the results from each of the individual five investigations. Detailed descriptions of specific Wild 2 encounter first results are expanded in other papers.

1.1. Comet Wild 2

[3] Wild 2 is a Jupiter family comet. Prior to 1974, the comet orbited between a perihelion at 4.9 AU and aphelion at 25 AU [Sekanina and Yeomans, 1985]. In 1974, the comet had a close encounter with Jupiter that dramatically changed its orbit. The comet now has a perihelion distance of 1.58 AU and an aphelion near Jupiter's orbit at 5.2 AU. Since that time, Wild 2 has made only five perihelion passages. In this sense, Wild 2 is relatively "fresh" comet

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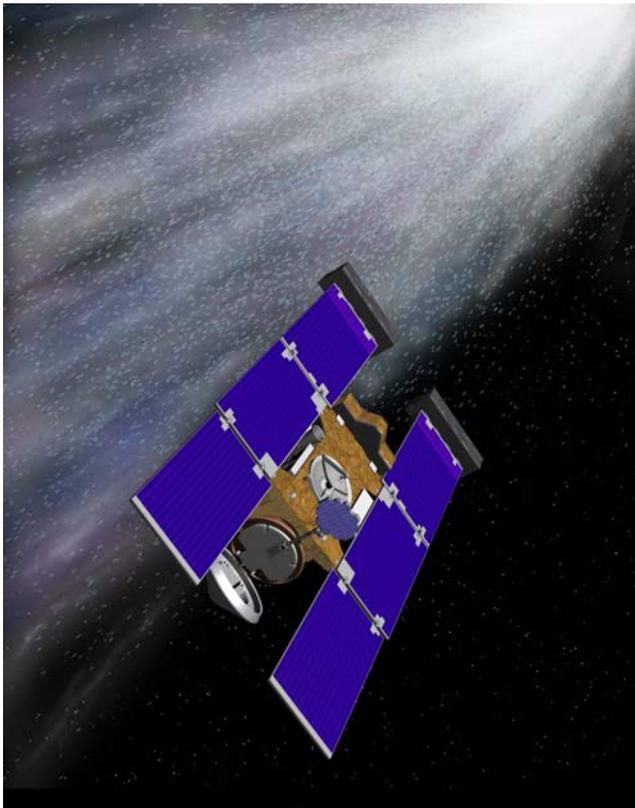


Figure 1. An artist drawing shows the Stardust spacecraft just before entering the Wild 2 coma. The rectangular box-like dust shields in front of the two solar arrays and the main spacecraft bus (gold-colored bus) protect the spacecraft from 6.12 km/s cometary dust impacts. The high-gain dish antenna is located at the center of the bus. The sample tray assembly is deployed from the Sample Return Capsule mounted on the backside of the spacecraft.

and its outer layers have only been subjected to moderate solar heating in recent history. As a Jupiter family comet, Wild 2's probable history includes formation and long term residence in the Kuiper belt, beyond 30 AU, and it may have transited among unstable orbits within the planetary system prior to its recent injection into the inner solar system. Wild 2 probably represents a sample of the Kuiper Belt source region of the solar nebula consisting of mineral, organic and volatile materials of both presolar and nebular origin [Sekanina, 2003; Hanner and Bradley, 2004].

[4] Wild 2's fifth apparition in 2003 was unfavorable for Earth-based viewing due to the small solar elongation angle. However, several key ground-based observations were made in the 3 weeks before the encounter. These observations offered critical updates in astrometry to assist with navigation and in photometry to provide an assessment of the level of Wild 2 dust activity at the time of the encounter. Astrometric data reduced the uncertainty in the time of closest approach, making it possible to optimize both the imaging sequence and the initiation of data capturing by in situ instruments. Photometric data in the thermal infrared from the 3-m NASA Infrared Telescope Facility on 14–15 December (A. Tokunaga, E. Tollestrup, and E. Volquardsen, unpublished data, 2003) and optical data from the 10-m Keck II

on 19–21 December (D. Tholen, unpublished data, 2003) were used to assess the amount of dust in the coma and were compared with predictions based on ground-based telescopic observations from the comet's 1997 apparition. The new data indicated that the dust cross section in the coma of Wild 2 for the weeks prior to encounter was only about half of that seen in 1997. On this basis, the Stardust science team decided to reduce the targeted flyby distance from 300 to 250 km. In August 2003, concerns about increases in the modeled flux of hazardous centimeter-sized particles had caused the encounter target distance to be moved outward to 300 km from the initial 150 km distance set at the 1999 launch [Brownlee et al., 2003].

1.2. Stardust Wild 2 Encounter

[5] An artist's rendition of the Stardust spacecraft encountering Wild 2 is shown in Figure 1. To prevent damage to the spacecraft from hypervelocity impacts by Wild 2 particles, the spacecraft is equipped with multilayer dust shields placed in front of both the spacecraft bus and two solar arrays. Only instrument sensors peek around the main dust shield as shown in Figure 2: the sample collector, the impact target of the CIDA, the DFMI sensors, the front surface mirror of the NavCam periscope and the three dust shields themselves served as impact targets to large dust sensed by the spacecraft attitude control system.

[6] Two years after launch on 15 January 2001, Stardust used an Earth gravity assist at the end of the first of a three-revolution heliocentric orbit, shown in Figure 3, to increase the semimajor axis and change its orbital inclination by 3.6° to better match the orbit of Wild 2. Toward the end of the second orbit, Stardust made a successful flyby of the asteroid 5535 Annefrank [Newburn et al., 2003b], affording a rare and invaluable in-space dress rehearsal for the Wild 2 encounter. The encounter with Wild 2 took place during the third and final orbit on 2 January 2004 at a distance of 1.86 AU from the Sun, when Wild 2 was 98.8 days past its perihelion. At the encounter, Wild 2 was orbiting at a

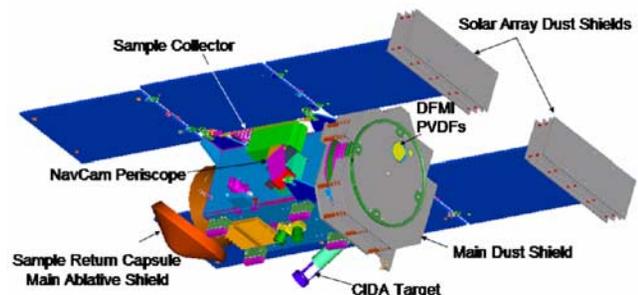


Figure 2. The bottom side of the Stardust spacecraft shows the locations of the in situ instrument components that are exposed in the dust stream: CIDA target, NavCam periscope, DFMI PVDF sensors and dust shields. The launch adapter ring is located at the center of the front face of the spacecraft bus. The sample tray assembly is peeking through the upper solar array and the spacecraft bus.

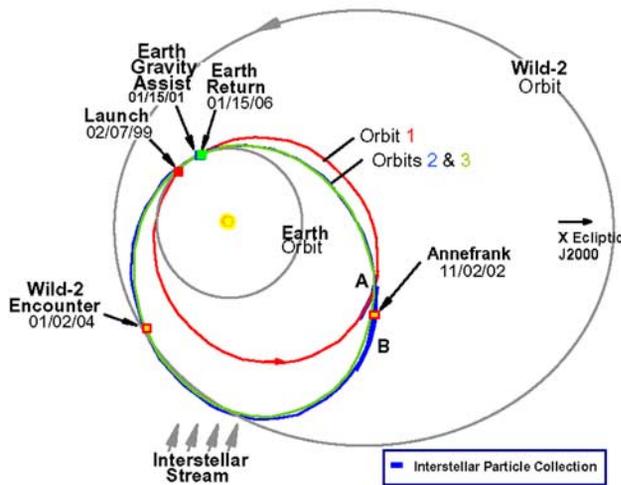


Figure 3. Stardust's three-revolution (red, blue, and green) 7-year trajectory is overlaid on the orbit of comet Wild 2 (gray). Stardust's major events, their dates of occurrence, and locations of occurrence are indicated by square markers on the trajectory.

heliocentric speed of 26.4 km/s and overtook the Stardust spacecraft at a relative resultant speed of 6.12 km/s; effectively the spacecraft was flying “backward” from the comet. The geometry at the closest approach to Wild 2 is depicted in Figure 4. Excellent engineering navigation allowed the cancellation of two planned trajectory correction maneuvers before the closest approach and at the closest approach where the spacecraft passed 236.4 ± 1 km from the Wild 2 nucleus. During the encounter, the attitude control subsystem maintained the spacecraft orientation to within $\pm 0.1^\circ$ to ensure that the dust shields were kept well within the $\pm 2^\circ$ angle needed to protect the spacecraft and the solar array panels from Wild 2 dust impacts. The engineering team invested significant time in developing and testing various fault scenarios to ensure the spacecraft could survive the encounter. All spacecraft systems performed nominally; there were no faults.

[7] In order to keep the Wild 2 nucleus in the 3.5° field-of-view of the NavCam at the closest approach, the spacecraft had to roll about the trajectory axis. At 6^m0^s before the closest approach, the spacecraft autonomously determined the required roll angle and executed a roll of 4.028° . Just before that time, the spacecraft switched from the spacecraft's high-gain dish antenna to the medium-gain horn antenna to maintain ground link by a carrier-only signal and stored all telemetry onboard for later transmission. The Wild 2 time of the closest approach was determined from the maximum NavCam mirror rotation rate to be 2 January, 19:21:32 UTC. At 6^m0^s after the closest approach, the spacecraft autonomously reversed the roll and locked onto Earth via its high-gain antenna, and proceeded to transmit the stored scientific and engineering telemetry over the next 34 hours.

2. Science Investigations at Wild 2

[8] Stardust conducted five science investigations during the Wild 2 encounter on 2 January 2004: (1) a sample

collection of Wild 2 coma particles, (2) the CIDA measurement of the chemical composition of small grains in the coma, (3) the DFMI recording of the dust impact rates and particle masses with polyvinylidene fluoride (PVDF) films and acoustic sensors, (4) the NavCam imaging of the Wild 2 coma and nucleus, and (5) a Dynamic Science tracking the Doppler residuals in the radio signal and the spacecraft attitude control sensors to constrain the mass of the comet nucleus and the size of large coma particles.

2.1. Comet and Interstellar Dust Analyzer

[9] CIDA provided by the German Space Agency (DLR) utilizes impact ionization mass spectrometry to analyze the chemical composition of particles after they are ionized on impacting the CIDA target [Kissel *et al.*, 2003]. CIDA recorded its first spectrum at 5^m53^s seconds before the closest approach and its last spectrum at 11^m51^s seconds after the closest approach. CIDA captured a total of only 29 spectra during the flyby [Kissel *et al.*, 2004]. The CIDA was in operation throughout the entire encounter period and its cumulative dust flux for the entire Wild 2 encounter is shown in Figure 5 along with three other in situ investigations aligned on the same encounter time axis. All CIDA instrument engineering parameters indicate a normal operation during the encounter without any anomaly. CIDA also captured the first cometary negative ion mass spectrum, N28, of cometary dust shown in Figure 6 along with one positive ion mass spectrum, P29, containing only a few lines which suggest that dust particles were small. Due to the relative low impact speeds (a factor of 10 lower than at 1P/Halley), more molecular ions are expected and they arise predominantly from the surface layers of the dust particles. So far, the data show little evidence of mineral grains; the spectra appear to be dominated by molecular ions of organic compounds. Some of the mass lines of the organic component, which could only be inferred at Halley, are

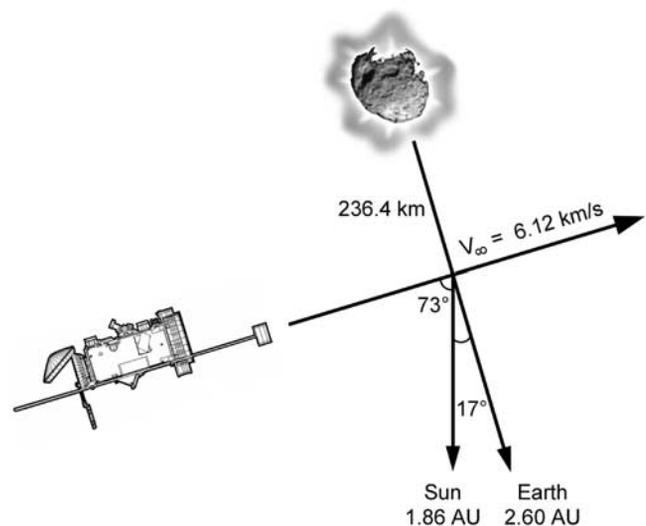
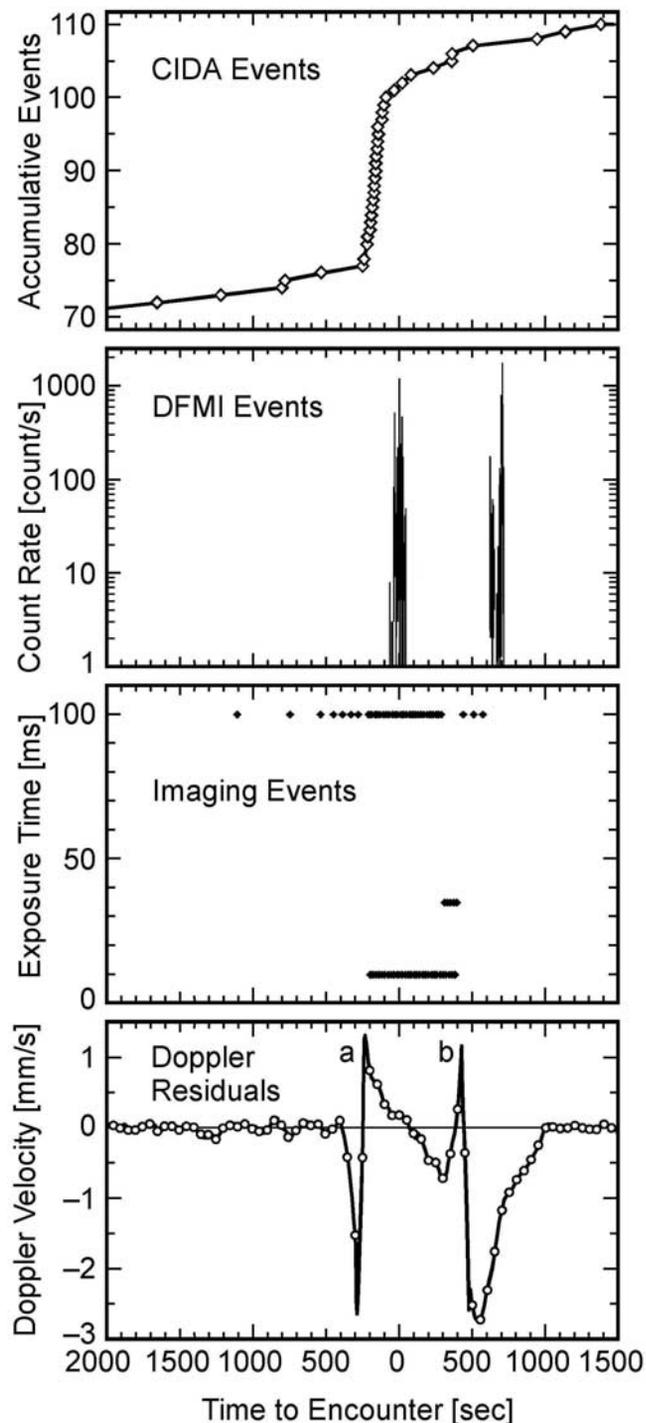


Figure 4. The instantaneous geometric relationships among Wild 2, Stardust spacecraft, the Sun, and the Earth at the time of the closest approach are depicted with the angular relationships and distances to the Sun; 6.12 km/s is the relative resultant speed of the Stardust spacecraft trajectory with respect to the comet Wild 2.

clearly seen. A number of possible explanations for approximately a factor of 100 fewer than expected count rate are currently being explored.

2.2. Dust Flux Monitor Instrument

[10] The dust flux and mass distribution along the spacecraft's flight path are important measures of the Wild 2 dust spatial and size distribution. The DFMI utilizes two types of sensors, polarized PVDF films [Tuzzolino *et al.*, 2003] and piezoelectric quartz accelerometers [McDonnell *et al.*, 1999] and classifies them into twelve distinct particle mass thresholds ranging from 10^{-11} to 10^{-4} g. The PVDF sensors



are located on a central upper portion of the front of the main dust shield. The front accelerometers is mounted on the lower half of the acoustically isolated spacecraft main bumper shield within the launch adapter ring. The second accelerometer is mounted on a circular acoustic plate attached to the first Nextel curtain behind the front bumper shield. Triggering the second accelerometer requires physical penetration of the centimeter-thick front bumper (graphite composite face sheets over aluminum honeycomb).

[11] DFMI was turned on for only a total of $33^m 21^s$ centered on the predicted time of the closest approach to ensure that a previously identified internal hardware fault would not interfere with its operation. Figure 5 shows a plot of the DFMI encounter impact rates. Unexpectedly, dust impacts were not uniformly distributed around the closest approach, nor was there a monotonic increase in the impact rate until the closest approach followed by a corresponding decrease afterward. Instead, the instrument indicated that particles appeared in intense bursts, with only a few to no impacts recorded between bursts. The cumulative particle mass distribution for the Wild 2 encounter is shown in Figure 7. The DFMI performance and detailed PVDF detections are reported [Tuzzolino *et al.*, 2004]. Seven particles detected by the acoustic sensors (the largest estimated to be 4 mm) even penetrated the front bumper shield, as described in a companion paper [Green *et al.*, 2004]. The apparent dust flux discrepancy between CIDA and DFMI are being investigated.

[12] The narrow time span of the impact bursts suggests a new comet comae dust release paradigm: release and subsequent disintegration of relatively large aggregate clumps, rather than the conventional model of individual release by surface volatile sublimation. Supporting evidences include astronomical observations of cometary phenomena such as striae, comet splitting, extended sources for volatiles, and radar echoes from large particles near the nucleus. Laboratory investigations of the behavior of volatile-rich powders in vacuum, icy-matrix soil mixtures, and low-temperature ices undergoing phase transitions and chemical reactions also contribute to an understanding of these phenomena. This model is presented in more detail in a companion paper [Clark *et al.*, 2004].

2.3. Imaging Science

[13] During the Wild 2 encounter between the antenna switchovers, the Stardust NavCam [Newburn *et al.*, 2003a]

Figure 5. In situ data from four Stardust investigations are plotted on the same time axis with respect to the closest approach to Wild 2. CIDA instrument registered dust impact events about the time of Wild 2's closest approach. Two dust bursts were recorded by DFMI: first about the closest approach and the second nearly 700^s after. Before the closest approach, NavCam toggled from 100 ms to 10 ms exposures. After the closes approach, a 35 ms exposure was added. The deviations of the Doppler residuals from a zero mean show the times of spacecraft thrusting for the two roll maneuvers at points a and b. The antenna switching occurred 6^m before the first roll maneuver (point a) from high-gain to medium-gain antennae and 6^m after the second roll maneuver (point b) from medium-gain back to high-gain antennae.

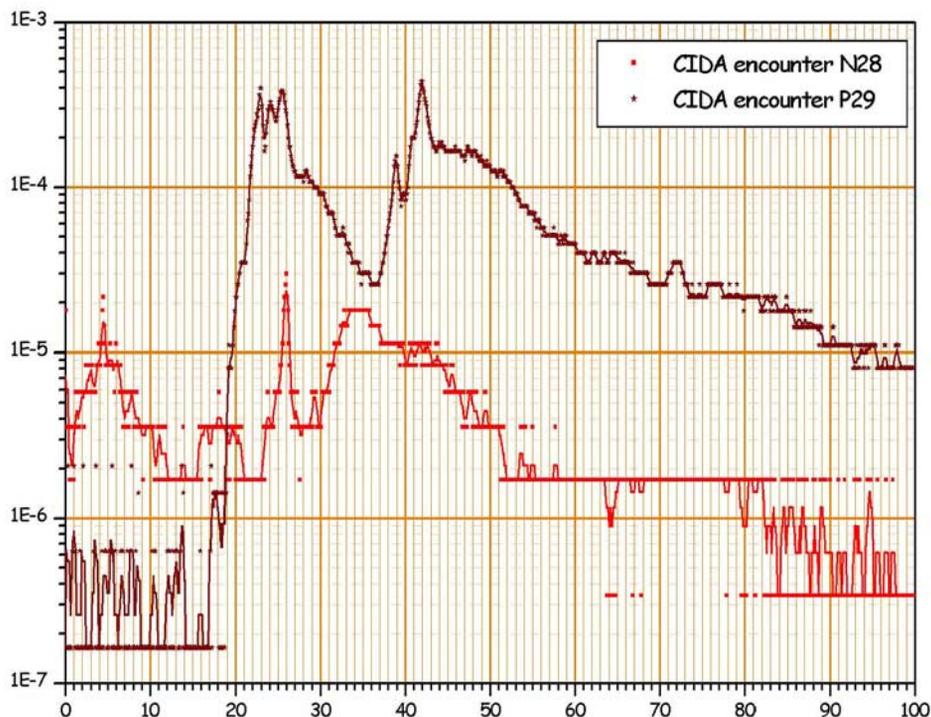


Figure 6. Spectra 28 and 29 are shown together captured at Stardust's encounter with Wild 2 on 2 January 2004 by CIDA. The detector current in arbitrary units is plotted in the ordinate, and ion mass in Daltons is plotted in the abscissa. The brown curve is a positive ion spectrum, being the last of the captured spectra. The red curve shows one of the first two negative spectra ever captured on comets. The number of lines of the spectra is few, indicating small particles.

acquired 72 images. The imaging sequence and their exposure times about the encounter are shown in Figure 5. Over the course of the 5 year cruise, the camera was plagued by recurring episodes of optics contamination. This contamination was successfully removed by on board heaters and the Sun's heat on the CCD radiator; the last heating cycle took place just 3 days before the encounter. Close encounter imaging was limited to two fixed exposure times: 25 ms for science imaging and 100 ms for nucleus tracking. Based upon the imaging experience on Borrelly, shorter exposure time would be desirable, e.g., 5 ms (L. A. Soderblom, unpublished data, 2003); just 11 days prior to the encounter, the imaging exposure time was reduced from the originally planned 25 ms exposures to 10 ms. Two spectacular approach and closest encounter images of the Wild 2 nucleus at 10 ms exposure are shown in Figures 8 and 9. The image resolution was better than 20 m/pixel at the closest approach. Longer exposures of 100 ms were taken in between 10 ms exposures to ensure the onboard nucleus image tracking software would maintain a good lock on Wild 2 nucleus. For these longer exposures, at times, the nucleus image bled due to saturation, but provided excellent images of fainter jets. An example of the spectacular jets just after the encounter is shown in Figure 10. A paper is being prepared on the Wild 2 imaging, the photometry, phase function and albedo of nucleus surface.

[14] A triaxial ellipsoidal model was used to fit the limb and terminator in all of the Wild 2 nucleus spanning

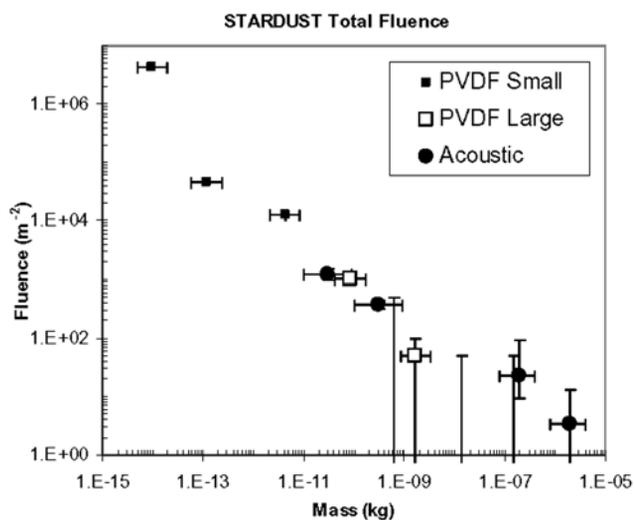


Figure 7. Cumulative mass distribution measured by DFMI with both the 20 cm² 6 μm and the 200 cm² 28 μm PVDF and Quartz piezoelectric accelerometer sensors at the Wild 2 encounter. The vertical error bars show the flux uncertainties for the higher mass particles, while the horizontal bars show the mass bin uncertainties.

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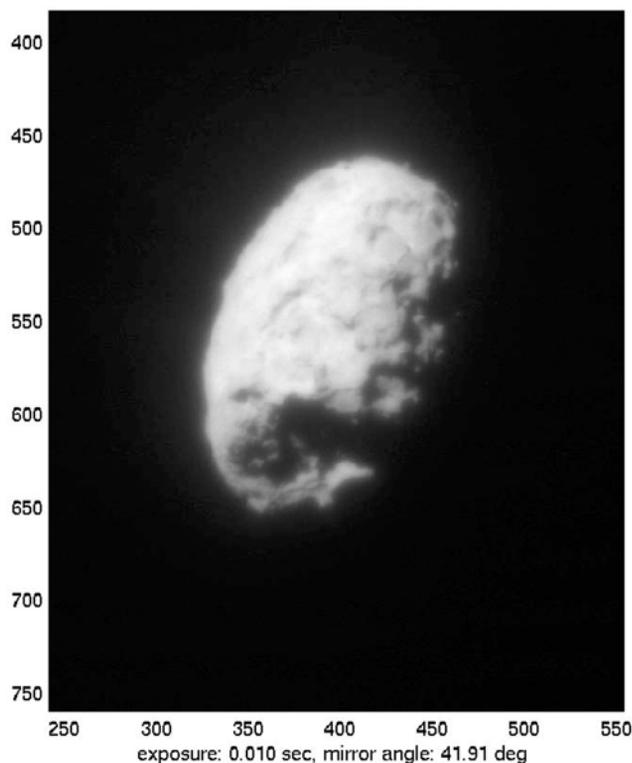


Figure 8. On approaching Wild 2 on 2 January 2004, the nucleus at 40° before the closest approach looks elongated. The numbers on the ordinate and abscissa are pixel position with respect to 1024 full frame.

180° of viewing angles and 110° of lighting angles. The principal radii of the comet were determined to be $1.65 \times 2.00 \times 2.75 \text{ km} \pm 0.05 \text{ km}$ at 1σ uncertainty. The illuminated limb is reasonably smooth with the exception of a few large depressions and spiky pinnacles on the limbs. The duration of the encounter was sufficiently short that the rotation period and axis of the nucleus cannot be definitively derived from the images. However, for a dynamically stable uniform density body, the rotation axis would correspond to the shortest axis. Assuming the shortest axis as the pole in defining the body-fixed coordinates of Wild 2, the pole has a right ascension α of 110° and a declination δ of -13° . These angles have uncertainties of $\pm 3^\circ$ at 1σ . A detailed discussion of the model fit and assumed pole position is contained in a companion paper [Duxbury *et al.*, 2004].

[15] The images of the nucleus surface are stunningly dramatic and show that Wild 2 is unlike any other solar system object previously studied. The visible landforms are distinctly better resolved than those of comets Halley and Borrelly and include craters, excavation zones, flat-floor depressions, surface crusts, landslides, lineaments, terraces, spires/pinnacles (100 m in height), steep cliffs, overhangs, and small bright patches which are potential vents. The nucleus does not have regolith normally associated with asteroids. There is evidence of the presence of both ancient and newly modified surfaces. A more detailed discussion of

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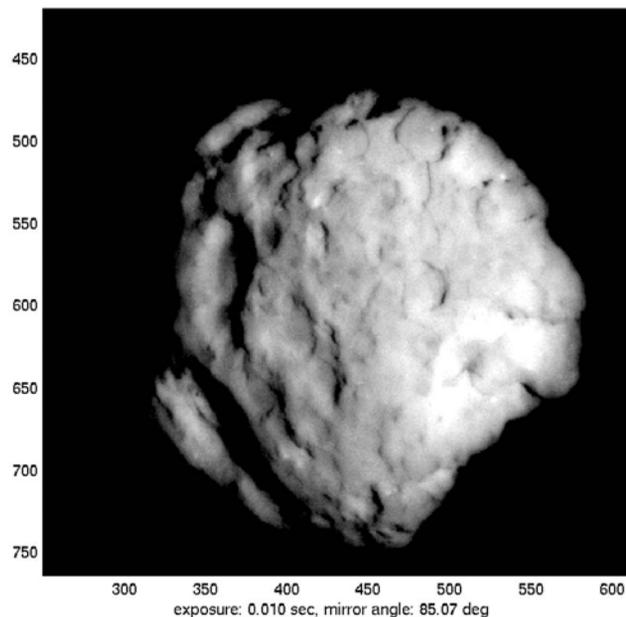


Figure 9. At post closest approach 20° , the Wild 2 nucleus appears more circular with much higher resolution revealing a diverse and rich variety of landforms: craters, excavation zones, flat-floor depressions, surface crusts, landslides, lineaments, terraces, spires/pinnacles, steep cliffs, overhangs, and small bright patches.

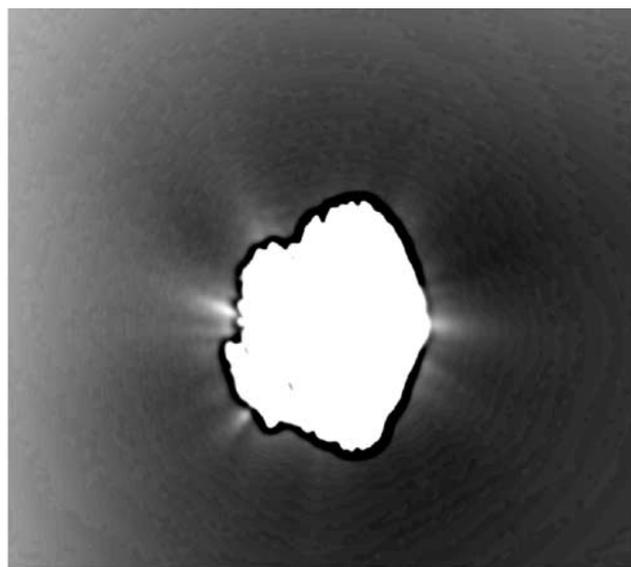


Figure 10. Before Stardust's launch, ground photographs showed only two prominent jets from Wild 2. This 100 ms exposure image of Wild 2 at the encounter shows jets emanated nearly around the entire perimeter of the nucleus. The Wild 2 nucleus itself has been blotted out and bled due to overexposure; however, this has enhanced the faint jets.

these surface structures and their implications with supporting hypervelocity laboratory simulations are described separately [Brownlee *et al.*, 2004].

[16] The orientations and source locations of twenty highly collimated and partially overlapping jets have been traced by applying a triangulation technique [Sekanina *et al.*, 2004]. Two jets are found to emanate from the dark side of the nucleus. A striking correlation has been found to exist between the times of the spacecraft crossing the sheets of the individual jets and the times of the sharp peaks recorded by the DFMI. The enormous peak of micron-sized particles encountered 2 seconds after closest approach is a signature of direct collision between the spacecraft and the leading front of an expanding jet. The expected anticorrelation between small and large dust grains in a peak can become a positive correlation for “old” jets for which the impacting grains are fragments of initially much larger, slowly expanding particles near the trailing end of an expanding jet. This temporal correlation makes it possible to determine that the comet rotates in a sense opposite that of its orbital motion about the Sun. Comparison with a preencounter model [Sekanina, 2003] suggests a possible nodding motion of the nucleus.

2.4. Dynamic Science

[17] The Dynamic Science investigation used the Doppler residuals of the X-band transponder and the spacecraft attitude control sensors to place an upper limit on the mass of Wild 2’s nucleus and on the size of the largest particles impacting Stardust [Anderson *et al.*, 2003]. The closed loop Doppler residuals are also shown in Figure 5. The transient frequency jump right at the point the antenna switched between high-gain dish and medium-gain horn provided verification that the Doppler data is synchronized properly with the spacecraft events. The upper limit of the Wild 2 nucleus mass is estimated as 5×10^{15} kg [Anderson *et al.*, 2004]. The spacecraft attitude control gyro and accelerometer sensors effectively turned the entire three dust shields into an active large dust particle detector with a cross section area of 2.05 m^2 . A confirmed trigger to the attitude control subsystem 15.5^{s} before the closest approach bounds the particle to be 20–80 mg [Anderson *et al.*, 2004].

2.5. Wild 2 Sample Collection

[18] These in situ encounter results are exciting in their own right and also provide estimates of the particle population captured by the aerogel collector and important context to the primary objective of Stardust: the collection of coma dust samples from Wild 2 and their return to Earth for detailed laboratory analyses. The exposed area of the Stardust particle collector consists of 1039 cm^2 of continuous gradient density silica aerogel and 153 cm^2 $101.6 \text{ }\mu\text{m}$ thick 1100 aluminum foil [Tsou *et al.*, 2003]. The aerogel collection area is divided into 130 individual $2 \text{ cm} \times 4 \text{ cm} \times 3 \text{ cm}$ rectangular cells and 2 trapezoidal cells. The sample collection tray assembly, deployed 9 days before the encounter and successfully retracted 5 hours after encounter, is now secured inside the Sample Return Capsule and poised for the journey home.

[19] These sample collectors are passive and give no in situ indication of particles captured. However, the number and size of collected particles can be estimated from

companion in situ investigations. From CIDA results, the aerogel collector would be projected to have captured only a very few large $15 \text{ }\mu\text{m}$ particles. However, the particle flux and particle size distribution derived from the DFMI measurements imply that the sample collector captured 2800 ± 500 particles larger than $15 \text{ }\mu\text{m}$ in diameter.

[20] The observed multiple jets indicate that Wild 2 released a substantial amount of dust from a significant number of localized active regions. Postencounter images taken through the NavCam periscope show significant degradation of the front surface aluminum mirrors, presumably due to reduced optical quality of the outer periscope mirror from a significant number of dust impacts. These in situ companion investigations indicate that the aerogel collector captured large numbers of cometary particles freshly released from the active regions of the comet Wild 2. The dust count disparity at Wild 2 between CIDA and DFMI is actively being investigated by both instrument investigators. The real ground truth of all of these estimates and discrepancies, however, will be determined during the preliminary examination of the returned samples on 15 January 2006. The parent molecule region of Wild 2 is not known; however, if hollow tracks are found in the aerogel cells, there are likely residual evidences of solid ice impacts [Mukai *et al.*, 1986].

3. Conclusion

[21] On 2 January 2004, Stardust successfully encountered with comet 81P/Wild 2 at a distance of $236.4 \pm 1 \text{ km}$. The first results of these investigations revealed new and surprising findings of comet Wild 2. It is anticipated that further analyses of these in situ data and stunning images will yield greater understanding of comets in general, Wild 2 in particular and possible solar system formational knowledge. The key details of cometary processing and solar system formational processes will be revealed in the micron-level laboratory analyses of the returned samples as demonstrated by the last three decades of analyses of collected Interplanetary Dust Particles. Detailed analyses of the returned samples captured in aerogel cells and aluminum foils will provide key compositional, morphological, isotopic and organic information on Wild 2 dust and will undoubtedly provide additional ground truths to further analyses of these in situ encounter measurements. These exciting and unexpected discoveries resulting from Stardust’s encounter with Wild 2 offer a wealth of new scientific insights into comets and a glimpse of the nature of early solar system formation and processes.

[22] **Acknowledgments.** The engineering teams at Lockheed Martin Space Systems and Jet Propulsion Laboratory operated the spacecraft faultlessly at the Wild 2 encounter. There were no faults during the flyby. The Stardust navigation team performed also superbly obviated two trajectory correction maneuvers. For this very successful Wild 2 encounter, we are deeply grateful to these engineering teams and support personnel. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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